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Detailing masts

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Abstract

As the efficiency and appropriateness of the structural membranes depends to a large extent on the supports, a research has been launched on the current design and the possibilities of optimizing the sections and the detailing are presented according to the typology established by the European Design Guide [1].

Keywords: masts, membrane structures, detailing

1. Introduction

Structural membranes need to be supported and tensioned by structural elements that condition the form and behaviour, affect the supposed lightweight appearance, and, in many cases, end up costing more than the membrane itself. As the most used supporting structural element is the mast, a research has been launched on its typology and detailing to improve efficiency and compatibility.

An extensive analysis of existing masts has been conducted to establish a typology, starting from the one mentioned on the "European design guide for tensile surface structures" [1], together with the formulation of strategies aimed at optimizing the design. Both concepts are profusely illustrated with selected examples drawn from the own experience and the documentation kindly provided by the authors, including visits to the sites and literature.

2. Antecedents

Masts were not new when tensile structures were significantly developed starting from the middle of the twenty century. Many other applications such as sailboats (fig.1 to 4), suspended and cable-stayed bridges, tents, cable suspended roofs and antennas had used and developed them considerably.

Figures 1,2: Running rigging on square sails [2]. Figures 3,4: Pilot's boat "Santa Eulàlia", Barcelona.

3. Typology

A typology based on the position related to the membrane includes:

a) boundary masts that support the edges at corner points. They are usually inclined to follow the resultant direction of the forces coming from the edge cables and going to the anchor ties. They can also be cantilevered when interferences coming from anchor ties are not permitted (fig.5).

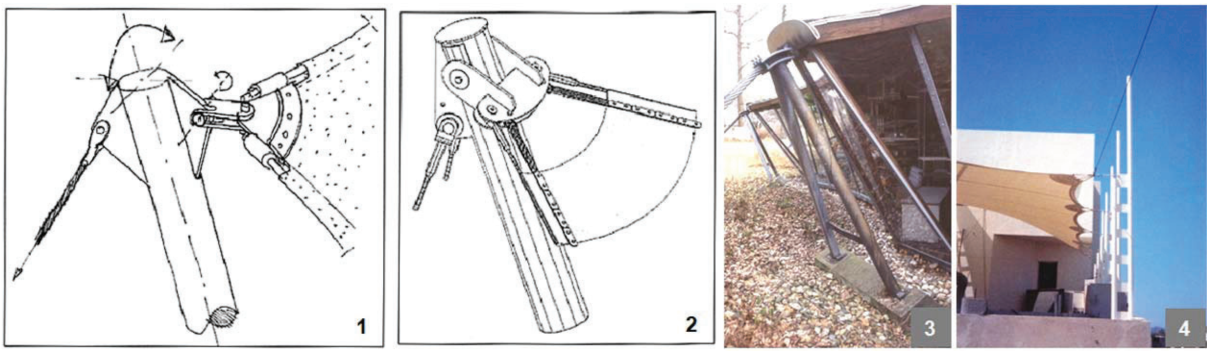


Figure 5: *Supported high points by external masts*. **1, 2** The connection with the peripheral masts can rotate around the horizontal, vertical axis or both. It is usually used for pre-tensionning. **3** A-shaped perimeter mast hinged at the base (IL Institute, Stuttgart). **4** Self supported perimeter mast. Stay ropes are not required.

b) internal masts surrounded by the membrane and resting directly on a base plate (fig.6) or floating/flying on steel cables that push them upwards (fig.7).

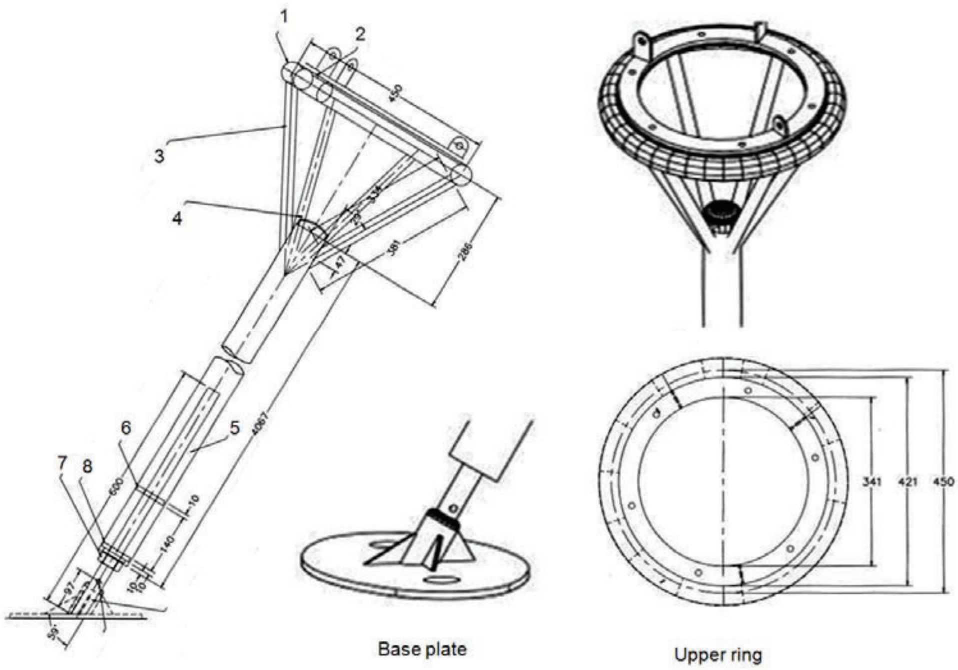


Figure 6: Central supporting mast of the Parc Astérix Dolphinarium, Plailly. It is achieved by a ring on top stabilised by guy cables and (semi)hinged at the base to relieve bending moments. A threaded assembly of the base allows for adjustment of the height and introduce prestress. The membrane is secured to the top of the mast by bolting between the ring and a circular plate. Notice the ring made of a Ø48,3 x 2,9 CHS to avoid sharp edges that could damage the membrane. The tension is introduced by adjustment of the mast length together with the tensioning devices of corners and edges [3].

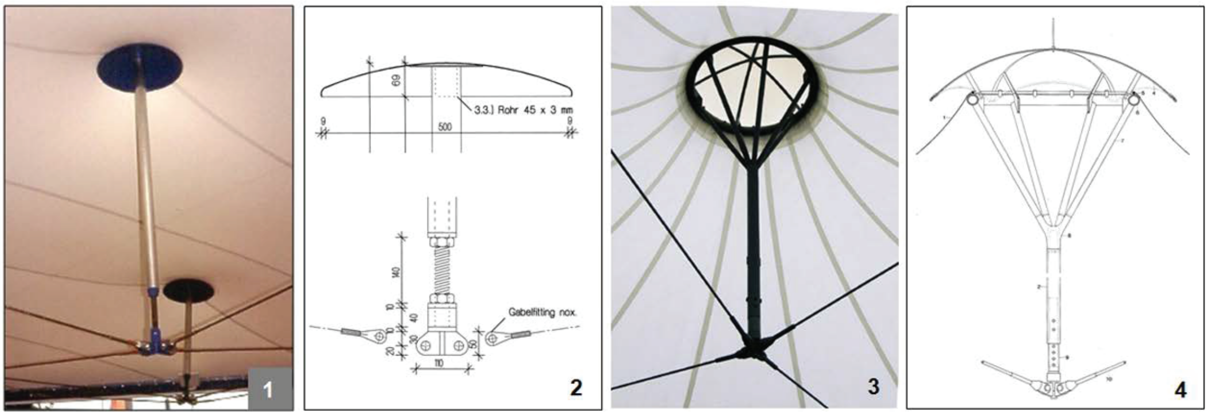


Figure 7: *Flying masts*. **1, 2** Flying masts supported on a cable net push up the membrane. They keep the covered space free of structural supports. A softening plate on the top of the flying mast enlarges the area of load distribution. Notice at the bottom the hinged fork cable-ends and adjustability of the length of the mast. **3**,**4** “A different approach to the connection between the flying mast and the membrane. The downward external loads applied to the structure are transmitted by bearing contact of the membrane on to the ring rather than by shear transfer through clamp bolts” [4].

c) external masts located outside the enclosure, from which the membrane is suspended (figs.8,9).

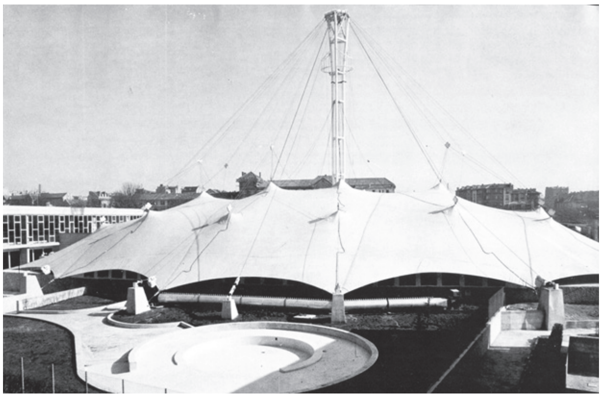


Figure 8 (left): R.Taillibert, 1966: Boulevard Carnot Swimming Pool, Paris. Figure 9 (right): R.Piano, 1991: Il Grande Bigo, Genova

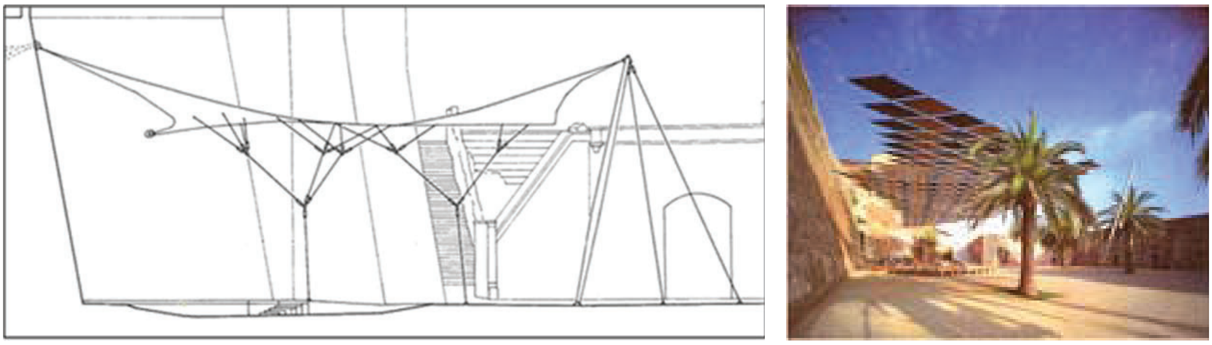


Figure 10: The tapered masts prevent from looking oversized compared to the whole structure and the site. J.A.Martínez & E.Torres with Llorens & Soldevila, Architects, 1991: Es Baluart, Palma de Mallorca

4 Shaft

The three types of mast accept different strategies to cope with over-dimensioning imposed by buckling on such long elements. They include the use of circular hollow steel sections (because of their efficiency in compression and torsion, minimal surface area to be protected, minimal wind resistance and availability) improved by tapering (fig.10), trussing (fig.11), tying (fig.12) or coupling (fig.13 to 15).

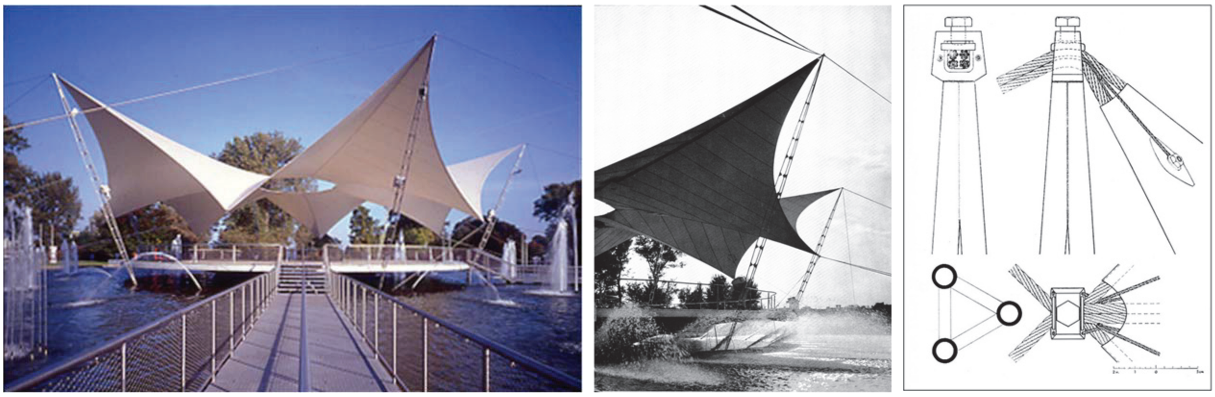


Figure 11: F.Otto & H.Spandow,1957: Dance Pavilion, Federal Garden Exhibition, Cologne. The masts are constructed very light and slender and, in addition, there are no gussets on the upper part of the masts, which means that the tops are not big-headed.

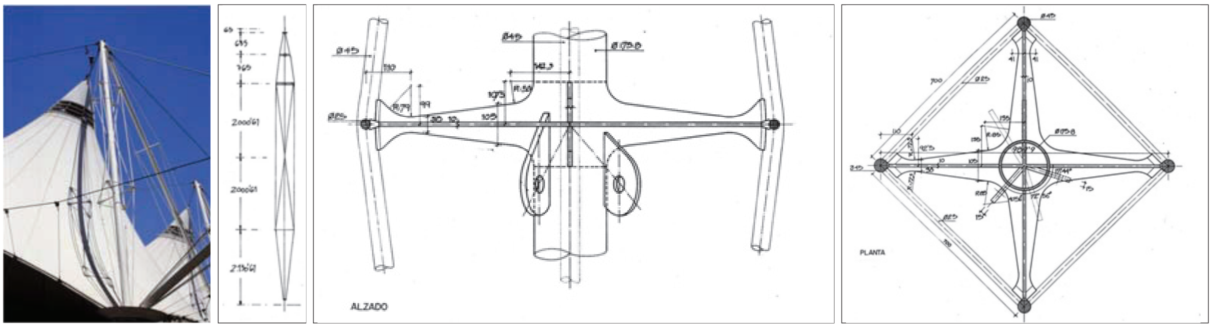


Figure 12: J.M.de Prada, 1992: “Palenque”, Sevilla Expo. Cross-trees 10 mm thick and ties Ø 25 mm lighten the mast by reducing the buckling length from 7,60 m to 4 m so that a CHS of 115 x 7 mm is enough.

Figures 13, 14, 15: Coupling or clustering the masts make them thinner. Slim tubes look more elegant than a single bulky cylinder. Figure 10: M.Hopkins 1985, Schlumberger Research Laboratory, Cambridge. Figure 11: Ph.Cox 1988: Darling Harbour Exhibition Centre, Sydney. Figure12: A.Brookes 1992, East Croydon Station, London [5].

5 Mast ends

Apart from the section of the shaft, its ends also have a considerable impact on cost, appearance and ease of installation.

5.1 High points

Upper ends can be in the form of circular rings, humps, loops or scalloped cables (figs. 16 to 20).

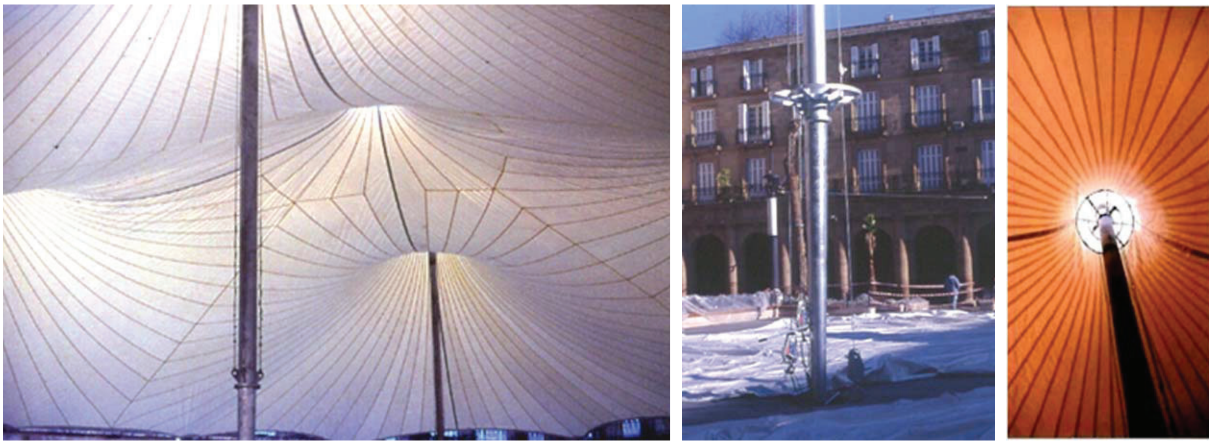


Figure 16: Llorens & Soldevila, Architects with IASO, 1990: Plaza Nueva, Bilbao. The membrane is raised along the mast by a circular ring driven by pulleys from the ground. The ring provides the perimeter length of material required to support the load not exceeding the breaking strength. The connection between the membrane and the ring can be considered a rigid edge, bearing in mind that a rigid connection is hardly compatible with the flexibility of the membrane. Here, the membrane can be prestressed from outside the ring and through the ring itself via its adjustable diameter and the pulleys [6].

Figure 17: "Jaima", the humped tent of the Berber tribes, Atlas Mountains. It is a single-family shelter including cattle, modular in construction, limited in size to the carrying capacity of the family camel (which, with the family goats, provides the hair from which the tent is woven), measuring around 20 by 40 feet and weighing about 360 lbs. The supporting hump-like high points are formed by poles topped by mushroom-shaped heads. The woven fabric acquires an anticlastic curvature except in the areas above the supporting humps [7].

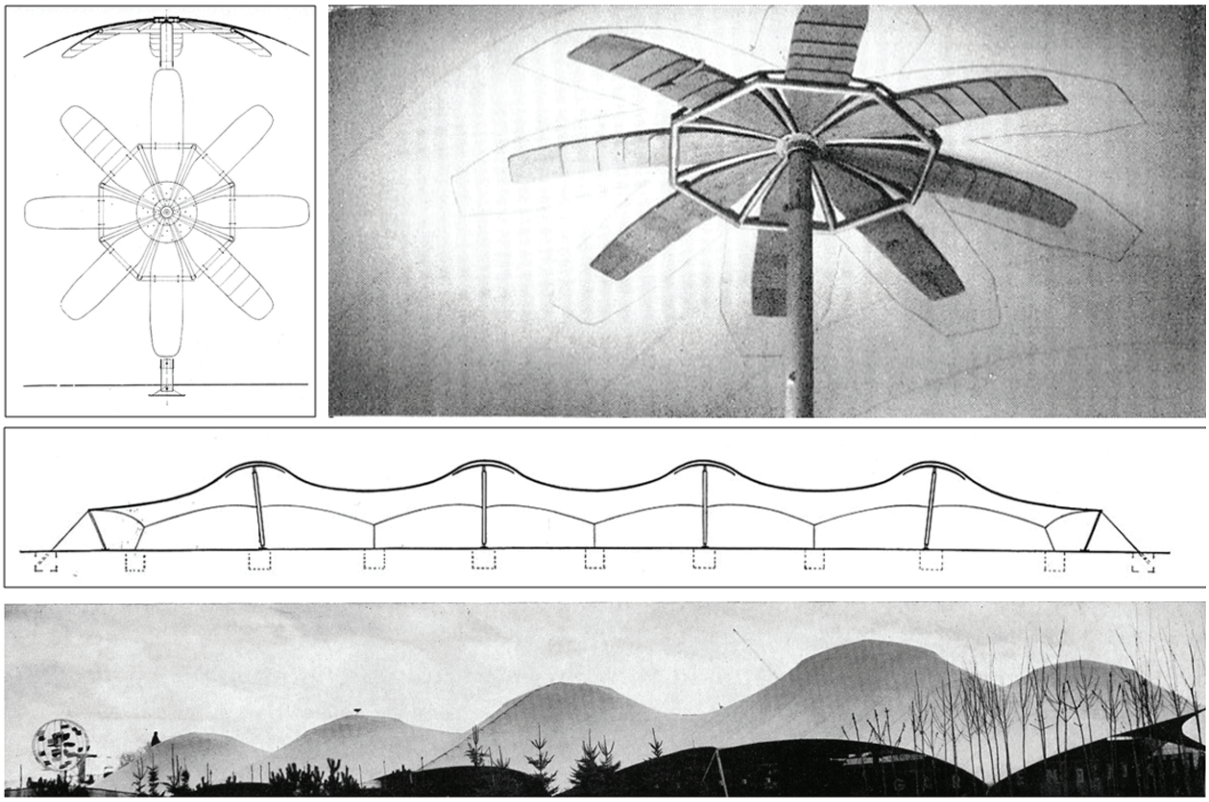


Figure 18: The hump-like high points of the tent at Hamburg International Garden Exhibition are formed by masts which have heads with flexible lamellae across which the membrane is stretched. The resilient head of each mast is 4 m in diameter and consists of radially disposed plywood blades which function as springs and are supported by a CHS with tubular spokes. A welded-on dished steel plate over the blades serves as an abutment for the latter. Each spring blade consists of five glued 8 mm thick layers of wood. Plywood is more suitable for the purpose than ordinary wood because its elasticity is more uniform. An important feature is that the deflections at the ends of the blades are very large in order to achieve smooth and uniform transmission of the force of the membrane.

The tubular poles have a total length of 5,5 m and are 180 mm in diameter. At the top and bottom they are provided with short telescopic tubular sections for adjustment springs. The latter are so designed that they transmit a prestressing force of 2,5 T to the membrane and also prevent the poles being subjected to excessively large compressive forces. The springs also compensate for the continual variations in length of the roof membrane which are caused by variations in humidity. The membrane stresses are thus kept approximately constant [8].

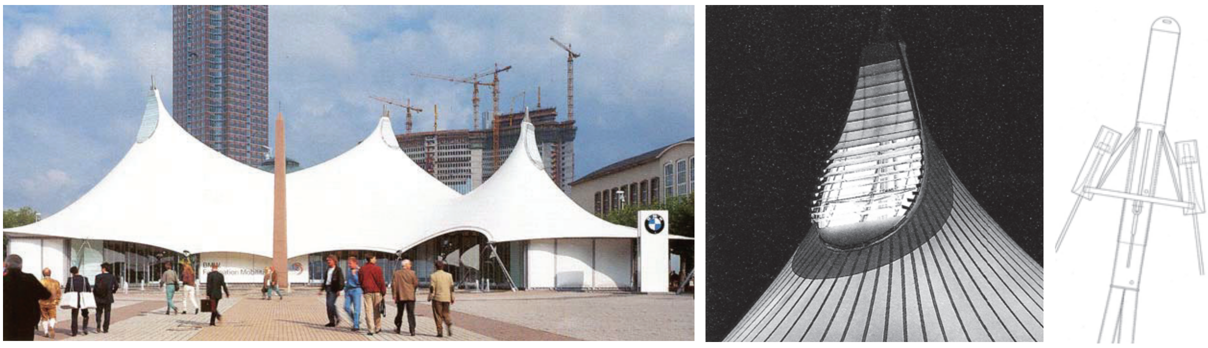


Figure 19: Frei Otto's favourite type of high point. Looped connection of membrane to masthead. Exhibition pavilion in Frankfurt, 1995 (Sobek und Rieger, Sttutgart with D.Wakefield, Bath) [9].

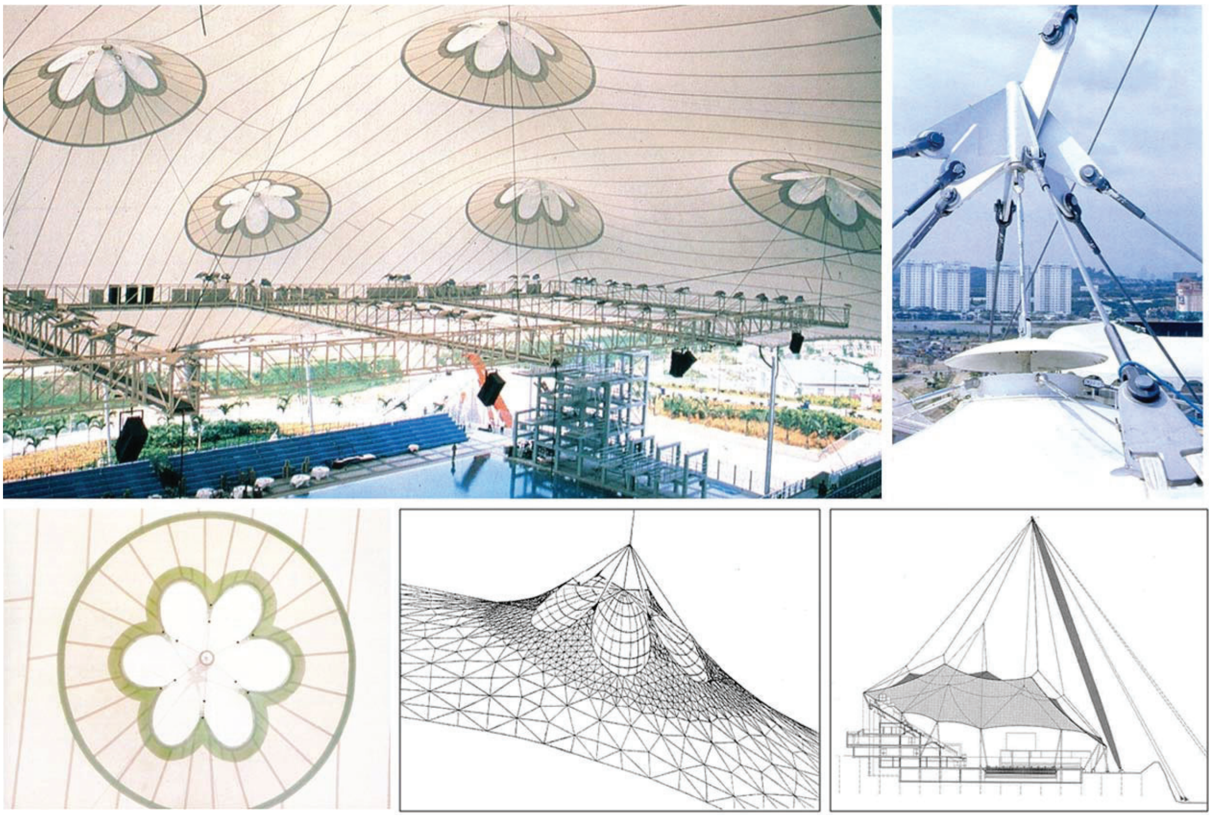


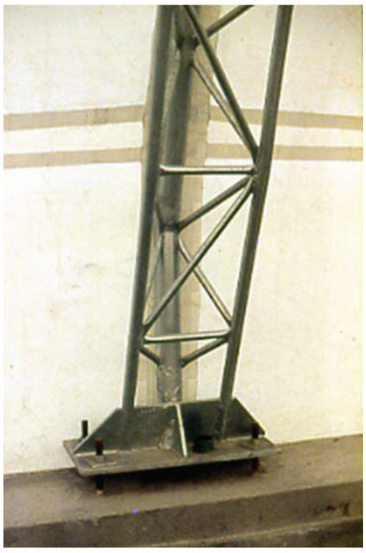
Figure 20: Widleplan Consulting with sbp, 1998: Commonwealth Games Swimming Pool, Kuala Lumpur. Scalloped high points. The cusp points of the belt are suspended from above by six straight cables and the central hole is closed over with a warped membrane panel [4].

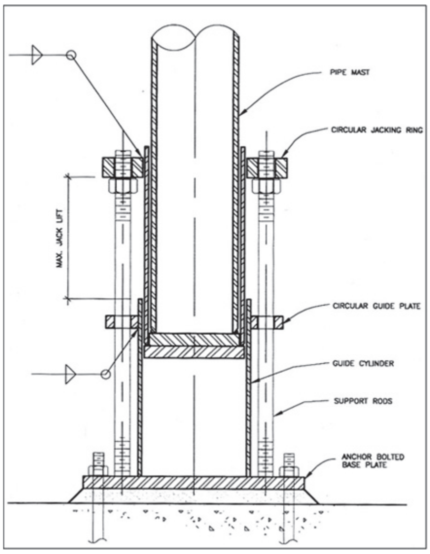
5.2 Mast-base plates

Mast-base plates transmit compression (and shear) forces. They have to be designed carefully because they can easily result in a bulky element standing in the centre of the main visual field of the users. Mast-base plates transmit compression forces. They usually stand in the centre of the main visual field of the users. People regard them as being a main part of the structure. They are fixed or pinned about one or two axes.

Figure 21: The base of the mast is pinned about two axes (Courtesy of N.Goldsmith). Figure 22: Spherical base plate (Courtesy of S.Bertino). Figure 23: Spherical base plate. Toll gate, Manresa motorway.

Fixed bases allow for stability without guying cables, but they are not suitable if lateral loads result in bending which require an increase in the size. Pinning about one axis is typical for masts located at the perimeter which are tied by cables anchored to the foundation. If rotation may occur about two axes, two-degree of freedom bases, such as spherical connections, are used (figs.21 to 23).





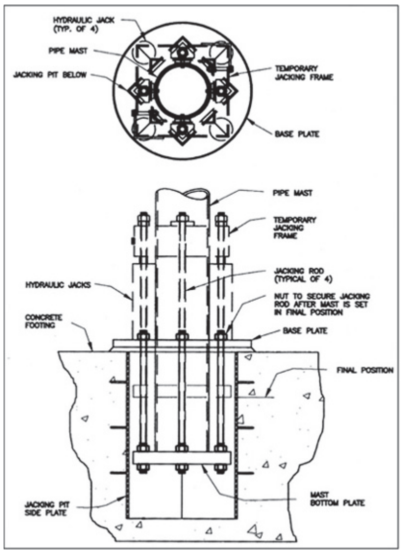


Figure 24: Base plates introduce pretension (Courtesy of M.Majowiecki). Figures 25, 26: Masts raised into position with portable hydraulic jacks [10]

7 Conclusion

Structural membranes, if not designed as such, require an imposing steel structure. As far as the masts are concerned, it is possible to achieve more efficient solutions optimizing sections, combining appropriate types, sections and profiles resorting, for example, to tapering, trussing, tying or coupling. Care has also to be taken in detailing to attend to the requirements of design and installation, avoiding bulky bases and big-headed tops.

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